Water budget of Skærsø, a lake in south-east Jylland, Denmark: exchange between groundwater and lake water

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The European Union's Water Framework Directive aims to achieve a 'good' ecological status for groundwater bodies, for groundwater-dependent terrestrial ecosystems, and for aquatic surface water bodies by the year 2015. In Denmark, this goal will most likely not be fulfilled within such a short time frame due to the current poor ecological condition of Danish lakes (Søndergaard *et al.* 2008). However, public concern about the protection of aquatic environments has increased, and so has interest in improving lake water quality by reducing nutrient loading. Effective and sustainable lake restoration and conservation depend on the ability to (1) point out sensitive catchment areas for the lake, (2) estimate its total water and nutrient budgets and (3) relate observed differences in seepage rates to the abundance and distribution of macrophytes in the lake and to the topography and land-use of the surrounding terrain. In seepage lakes, i.e. lakes without inlets or outlets, the influence of the surrounding terrain, regional hydrogeology and lake geometry on the overall lake water budget has been studied in some detail (Krabbenhoft *et al.* 1990; Anderson & Cheng 1993; Cheng & Anderson, 1994; Kratz *et al.* 1997;

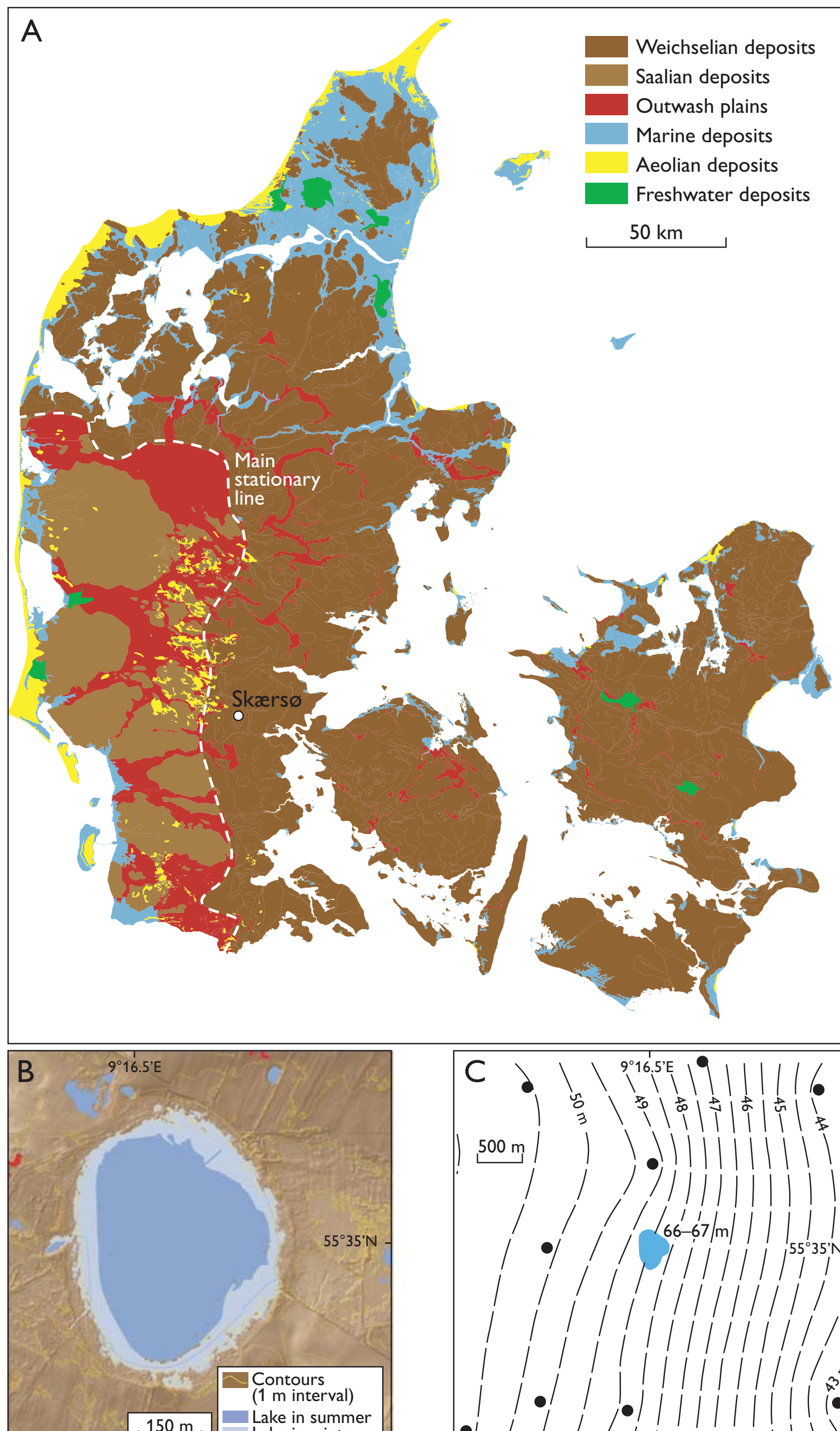

Fig. 1. **A**: Location of Skærsø east of the main stationary line in Jylland. **B**: Lake area in summer (dark blue) and winter (light blue). **C**: Map of the lake Skærsø area showing the groundwater level of the regional aquifer and the water level of Skærsø. Black dots show the locations of wells used to construct the map.

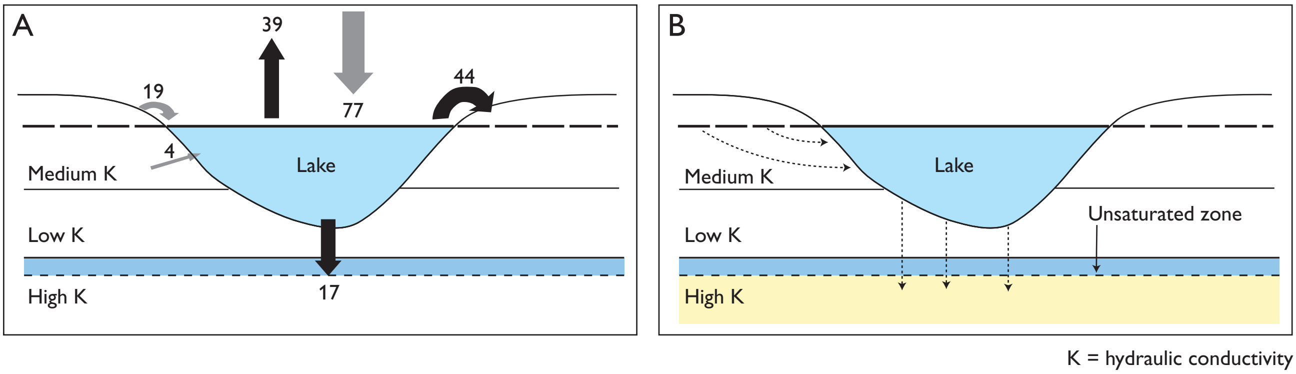

Fig. 2. **A**: Preliminary model of the water balance of Skærsø. Grey arrows show influx, black arrows loss. Numbers in per cent. **B**: Conceptual hydrogeological model of a perched lake disconnected from the underlying aquifer.

Winter 1999; Townley & Trefry 2000). However, little effort has been made to understand and quantify how riparian zones (wetlands) surrounding lakes may control the water flow and nutrient transport to the lakes. Although groundwater inflow to seepage lakes is suspected to be smaller than inflow from drainage ditches, it may still account for a significant nutrient influx.

This paper focuses on field work carried out 2007 and 2008 at Skærsø, a lake in the upper part of the Kolding Å catchment area in south-east Jylland (Fig. 1A). Field studies at Skærsø have shown that seepage can vary on different scales in both space and time. The purpose of this study is to link measurements of lake seepage rates and lake precipitation or evaporation to the catchment hydrogeology. The project is conducted by the Centre for Lake Restoration, which includes participants from University of Southern Denmark, National Environmental Research Institute, University of Copenhagen and Geological Survey of Denmark and Greenland.

Towards a lake typology

The Centre for Lake Restoration is developing a typological classification of Danish lakes using a multidisciplinary approach that integrates interactions between groundwater and lake water. The classification is based on geological, hydrological, hydrogeological, geomorphological, botanical and chemical aspects. The botanical part focuses on plant indicator species in the lakes, and the chemical part addresses water and sediment chemistry. Two or three main lake types are currently distinguished on the basis of geological, hydrological, hydrogeological and geomorphological criteria. New lake types will probably be defined in the coming years as biological and chemical indicators are also included in the classification.

Location and setting of Skærsø

Skærsø is located a few kilometres east of the main stationary line that formed during the last glacial maximum around 20 000 years ago. The lake is situated in the upper part of the

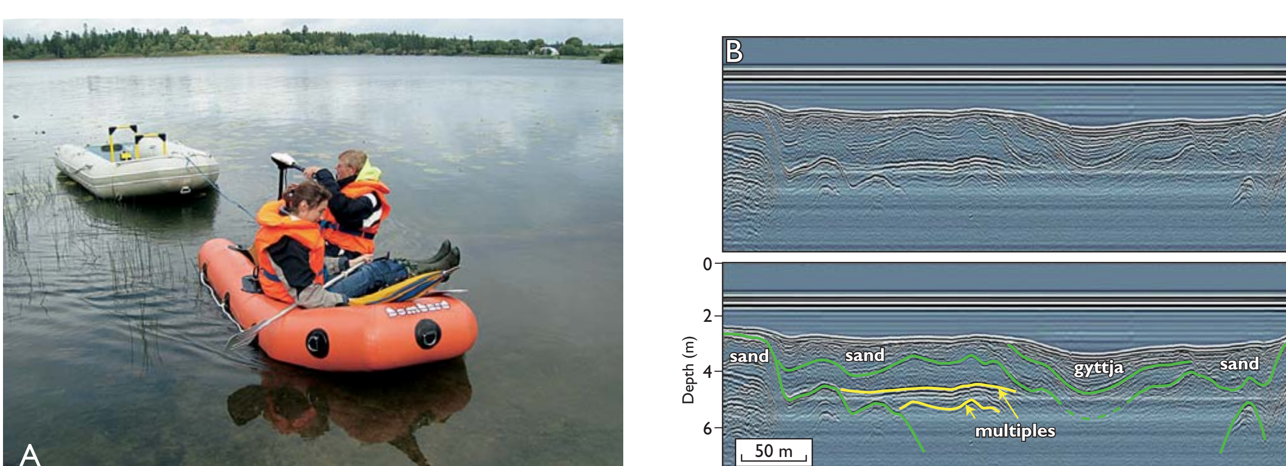

Fig. 3. **A**: Mapping of lake sediments using reflection ground penetrating radar (GPR). The radar equipment is contained in the grey rubber boat. **B**: An example of a GPR reflection profile with a preliminary interpretation.

Kolding Å catchment area (Fig. 1A) that is dominated by glacial and glaciofluvial deposits. Around Skærsø a 2–7 m thick sand layer overlies an approximately 10 m thick clayey till that is underlain by a regional sandy aquifer. The riparian zone around Skærsø has a width of 30–50 m and a thickness of 0.1–0.5 m, and consists of organic-rich fine sand and silt. The water table of the lake varies seasonally about 0.5 m, and in the winter or early spring the riparian zone around the lake is flooded (Fig. 1B). During flooding, organic particles and solutes are transported to the lake and cause a significant decrease in the transparency of the water. Below Skærsø, the groundwater table of the regional sand aquifer is 48–49 m above sea level, whereas the surface of the lake is 66–67 m above sea level. This difference indicates that there is a hydraulic connection between the lake and the regional aquifer (see below and Fig. 1C).

The area of Skærsø is approximately 16 ha , and its average water depth is 1.5 m, with a maximum depth of about 8 m. It is characterised as a mesotrophic, low-alkaline, clear-water lake. Until the 1980s, Skærsø was a clear-water heath lake, dominated by submerged macrophytes including *Lobelia dortmanna* that grew to a depth of 1.5 m. At the end of the 1980s, Skærsø suffered from organic-rich, acidic, unclear water, resulting in almost complete disappearance of the submerged macrophytes. After almost 19 years of unsuccessful attempts at lake restoration, the conditions in Skærsø are still deteriorating. A recent study showed that changes in light conditions in the lake are not as strongly coupled to changes in the external nutrient loading as expected (Frandsen & Stæhr 2007). Changes in the hydrology of the riparian zone have led to a seasonal flush of dissolved coloured organic matter into the lake which causes decreased water transparency, decreased light penetration and release of nutrients. However, the mechanisms that affect water transparency require further investigation.

Hydrogeological model

The hydrogeological model of the lake is characterised by the setting of shore and wetland (the riparian zone) with an upper, local groundwater aquifer in sediments of low to moderate permeability showing low hydraulic gradients. The deeper part of the lake is probably connected to a lower permeable layer with high hydraulic gradients (Fig. 1C). Because the surface of Skærsø is almost 20 m above the hydraulic head of the regional sand aquifer, we expect leakage of water from the lake through its bottom into the underlying regional aquifer.

The water supply to Skærsø is dominated by precipitation (77%) and inflow from the catchment area (19%). A limited portion (4%) comes from the shallow, local groundwater aquifer. Water flux from the lake is dominated by outflow via outlets (44%; mainly an artificial ditch) and evaporation (39%). We suggest that the remaining 17% is lost by leakage to the underlying aquifer (Fig. 2A). Thus Skærsø can be conceptualised as a perched lake, a lake which is disconnected from the underlying aquifer by an unsaturated zone between the lake bottom and the aquifer (Fig. 2B).

Ground penetrating radar

In order to investigate the structure and thickness of the sediments below the lake, a ground penetrating radar survey was carried out (Fig. 3A). Thick layers of organic-rich sediments such as lake mud (gyttja) or peat generally reduce groundwater seepage, whereas sandy sediments can promote interaction between groundwater and lake water (Fig. 3B). Ground penetrating radar can help to identify areas of potential groundwater seepage, which may then be verified using more traditional point measurements such as coring. The application of ground penetrating radar to map lake sediments is new in Denmark, and the interpretation of the radar profiles is still uncertain and needs to be checked against data from coring. However, according to our preliminary interpretation of the radar data, sandy sediments are widespread below the lake, whereas gyttja is probably restricted to a small area (Fig. 3B).

Multidisciplinary approach to estimate the groundwater flux

Seepage to or from Skærsø to the upper, local groundwater aquifer was measured using various tracers (heat, stable isotopes), direct measurements of water flux, as well as nutrients sampled from piezometer transects. The combined use of different tracers and methods at different scales provides a good understanding of the physical, chemical and biological behaviour of the entire lake. Figure 4 shows three types of field equipment that were used to quantify the flux from the local aquifer to Skærsø, and the estimated groundwater fluxes (specific discharges) to Skærsø are summarised in Table 1.

The flux values estimated by the three different methods are not consistent. The highest estimated fluxes (using the Darcy

Table 1. Groundwater discharge into Skærsø

Method	Flux	Specific discharge (m/sec)
Seepage meter	q_{seep}	$10^{-7} – 3 \times 10^{-7}$
Temperature	q_T	$10^{-8} – 10^{-7}$
Darcy[1]	q_D	$10^{-7} – 10^{-6}$

[1] $q_D = K \times i$, where K is the saturated hydraulic conductivity of the lake-shore sediment (i.e. fine sand and silt in the upper 2 m) equivalent to $K = 10^{-4} – 10^{-5}$ m/sec, and i is the hydraulic gradient measured by a potentiomanometer to about ± 0.01.

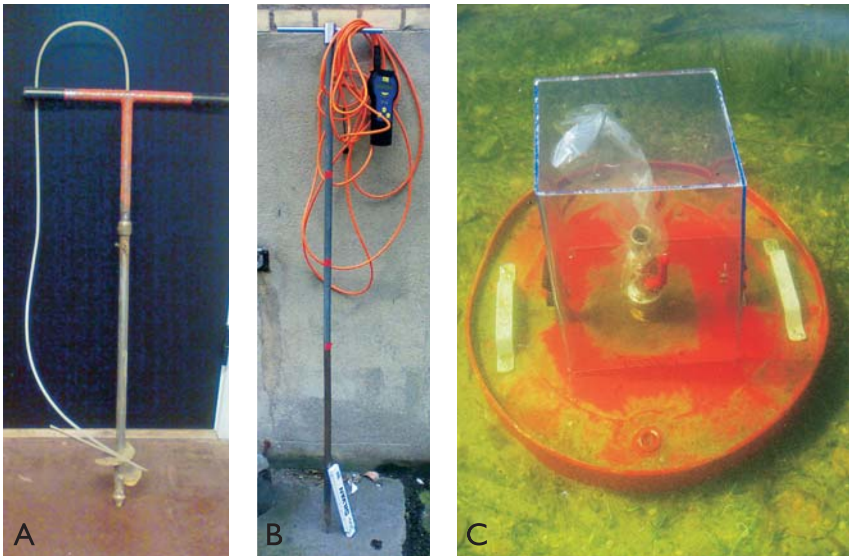

Fig. 4. Equipment used for field determination of groundwater seepage. **A**: Modified 1 m long potentiomanometer used to measure the water pressure in the subsurface (Winter *et al.* 1988). **B**: Multi-level, 1.25 m long temperature probe used to measure the temperature at multiple levels in the sediment (Schmidt *et al.* 2005). **C**: A steel drum seepage meter, 0.5 m in diameter, used to measure the flow of groundwater through the lake bottom (Lee 1977). From Nilsson *et al.* (2008).

(transect) method) are 10–100 times higher than the lowest estimated fluxes (using the temperature method). Despite this difference, the data indicate a low inflow from the shallow groundwater aquifer and, as mentioned above, we suggest that 4% of the inflow to the lake comes from the shallow aquifer, based on the average value obtained by the applied methods. We have no data on leakage through the lake bottom to the underlying aquifer, but we consider this process likely and suggest a flux value of 17% based on the difference between the other fluxes. However, this figure is highly uncertain. Especially the figure for the evaporation from the lake may be underestimated if investigations of other lakes in Jylland are considered. Nevertheless, we conclude that exchange between groundwater and lake water plays an important role in the water budget of lake Skærsø.

Acknowledgement

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